THE ROLE OF DEEP LEVEL TRAPS IN THE OPTICALLY CONTROLLED SEMI-INSULATING GaAs SWITCH

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ABSTRACT

A numerical solution for the transient photoconductivity in the laser-activated bulk semi-insulating GaAs switch has been obtained, in which the influence of EL2 and other traps on the optical generation rates and the recombination rates of free carriers has been determined. Calculated photocurrent pulses are compared with the experimental results of switching measurements under conditions of low laser intensity and low device electric field. The comparison shows that the EL2 model is sufficient to explain the large extrinsic photoconductivity which is observed. The dependence of the recovery on the various traps is discussed.

Both the free carrier and trapped carrier concentrations are described by a system of coupled rate equations, which is solved using a fourth-order Runge-Kutta method. The trap parameters used in the rate equations are obtained from recently reported values in the literature.

Both analysis and experimental results emphasize the critical role of traps in the design of optically controlled gallium arsenide switches.

INTRODUCTION

This paper models the role of traps in the generation and recombination of free carriers in the Nd:Yag laser activated semi-insulating GaAs switch, and predicts the temporal evolution of the photocurrent pulse as a function of the applied field, the laser intensity and pulse shape, and the switch circuit parameters. The computer simulation is compared with the results of optical switching experiments in which a Q-switched Nd:Yag laser is used to activate a semi-insulating GaAs switch under various conditions of bias voltage and laser intensity.

The experimental parameters of ultimate interest are the load current and voltage waveforms. The computer code solves for the load current and voltage using a simple circuit analysis based on a calculated switch resistance. The switch resistance is calculated from the geometry, the free carrier concentration, and the mobility. The free carrier concentration used for this calculation is obtained by solving a system of coupled rate equations using a fourth order Runge-Kutta method. These equations describe the generation and recombination of free carriers due to various mechanisms. This paper focuses on the mechanisms related to traps, in particular EL2, EL6, and HL10, and how well a simple model based on these traps predicts the experimentally observed photoconductivity in laser illuminated semi-insulating GaAs.

PHOTOGENERATION FROM THE EL2 DEEP LEVEL

There is strong evidence that, at intensities where two photon absorption is not significant, free carrier generation involving the deep level EL2 is more important than generation from any other deep level, and by any other mechanism, in the Nd:Yag activated semi-insulating (SI) GaAs switch.

There is evidence that the absorption at room temperature is predominantly due to either photoionization or photoneutralization of EL2, generating either a free electron or a free hole, respectively (ref. 1, 2). Optical cross-sections have been determined for these processes (ref. 2). It is apparent that the energy absorbed by the EL2 trap does not go into the excitation of an electron into a metastable state at room temperature. The EL2 trap plays a dominant role in photogeneration. However, it is not dominant in regard to recombination, where other traps also play a role.

The photogeneration mechanisms incorporated into the code include bleaching effects (effect of increasing electron vacancy of the EL2), as well as the influence of multiple reflections in the GaAs sample.

RECOMBINATION MECHANISMS

The likely recombination mechanisms in SI GaAs under high injection conditions are radiative band-to-band, auger, and non-radiative recombination via traps. As GaAs is a direct band-gap material, the direct band-to-band radiative recombination is large. Researchers indicate a coefficient on the order of 7.5 X 10^{-10} cm^3/s. (ref. 3). The contribution of this mechanism is difficult to determine as the recombination radiation can be re-absorbed by the material. At the higher carrier concentrations possible under high-intensity laser illumination, auger recombination becomes significant. The same researchers indicate an auger recombination coefficient on the order of 1.9 X 10^{-29} cm^6/s. From these coefficients, it appears that the primary recombination mechanism for carrier concentrations less than 10^{17} cm^{-3} is recombination via deep levels.

The EL 2 deep level is considered to be the dominant electron trap in SI LEC GaAs due to its high concentration and large capture cross-section. It is the most widely studied electron trap in GaAs because the GaAs, which is deliberately compensated with EL2, is used as the substrate for GaAs integrated circuits. Researchers report other electron traps in GaAs with large capture cross-sections (ref. 4). In particular, EL6 has been detected in bulk GaAs material. The EL6 trap is similar to and may be considered representative of a number of shallower electron traps, such as EL3 and EL5. The HL10 trapping

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1987	**N/A**	**-**

4. TITLE AND SUBTITLE
The Role Of Deep Level Traps In The Optically Controlled Semi-Insulating Gaas Switch

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Labcom, Electronics Technology & Devices Laboratory Fort Monmouth, New Jersey 07703

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

level is one of the few hole traps reported which is not conclusively related to an impurity, although vanadium is suspected. Also, its electron capture cross-section has been measured (ref. 5). As a deep level hole trap with high capture cross-sections for holes and electrons, the HL10 trap may be considered representative of deep levels introduced by trace metal impurities.

EL2 traps definitely exist in our material. We have measured them by optical absorption. It is likely that EL6 traps, or some other electron trap with similar parameters, is present. It is also likely that a hole trap similar to HL10, either related to trace impurities or of unknown origin, is present, perhaps HL10 itself. These are the three trapping levels we have used to model our material; EL2, EL6, and HL10.

TRAP PARAMETERS

In order to model the effect of traps in recombination and photo-generation, various trap parameters are required. For each trapping level, capture and emission coefficients for electrons and holes, and trap ionization energy and concentration are required.

EL2 TRAP PARAMETERS

The material used for the switch is SI GaAs grown by the liquid encapsulated Czochralski (LEC) technique in a boron nitride crucible. The high resistivity is obtained by growth with excess arsenic. Although its exact nature has not been conclusively determined, the EL2 defect is related to the arsenic antisite defect, perhaps in association with interstitial arsenic. The EL2 defect so introduced compensates for the residual shallow impurities, notably carbon, and possibly Be and Mg (ref. 6). Carbon is reported in high concentrations, up to 1.3×10^{13} cm^{-3}. Measurements of EL2 concentration by optical absorption (ref. 7) and by capacitance techniques on low resistivity material (ref. 8) indicate concentrations up to 1.7×10^{16} and 3.0×10^{16}, respectively.

The value used for the EL2 capture cross-section for holes was measured by Mittoneau et. al. (ref 5) using a modified ODLTS technique. They found a value of 2.0×10^{-18} cm^2 at 320 K. The temperature dependence of the hole capture cross-section was not measured. However, if it varies similarly to the electron cross-section, it drops about 15% in going to 300 K to 1.705×10^{-18}. The capture coefficients are determined from the cross-sections and the thermal velocities. The emission coefficients were calculated using the capture coefficients using the appropriate trap degeneracy factors, density of states for the valence and conduction bands, and trap energy level. Optical cross-sections were taken from ref 2.

HOLE TRAP PARAMETERS: HL10

Both the electron capture cross-section, 3.715×10^{-16} cm^2, and the hole capture cross-section, 5×10^{-16}, of the HL10 trap are large (ref. 5). Assuming that the trap ionization energy varies with temperature as the bandgap, and using a trap energy level of .83 eV from the valance band at 0 K (both, ref. 9), the trap ionization energy is .592 eV from the conduction band at 300 K. Capture coefficients and emission rates are calculated from the cross-sections using this value.

ELECTRON TRAP PARAMETERS (OTHER THAN EL2): EL6

The EL6 parameters were obtained from ref. (1). Assuming a temperature variation of the trap activation energy similar to EL2, the electron capture and emission coefficients were calculated from the given capture cross-section. The calculated trap ionization energy at 300 K is .197 eV from the conduction band. The capture cross-section for holes was not available. The hole trap parameters were calculated assuming a value similar to EL2.

TRAP OCCUPANCY

The thermal equilibrium occupancy of the trapping levels are important parameters which strongly influence the recombination rates, and so, the recovery characteristic of the photocurrent. Hall measurements on our material show a free electron concentration of 7.60×10^6. This corresponds to a Fermi-level .64 eV from the conduction band. The trap occupancy factors were calculated using this value along with the previously indicated trap ionization energies and appropriate degeneracy factors. Both the EL2 and the HL10 are pinned to the Fermi-level. It is estimated that the EL2 is 85% occupied, the EL6 is un-occupied, and the HL10 is 23.8% occupied, under equilibrium conditions. Our approach is similar to that presented in ref. (1). Our estimated EL2 occupancy is different because our value for the EL2 ionization energy at 300 K is 23 meV less.

RATE EQUATIONS

The rate equations used in the code describe the change in free carrier and trapped carrier concentrations as a function of time, incident photon flux, and material and trap parameters. They are in a standard form, similar to those found in ref. (10).

SWITCH RESISTANCE CALCULATION

The switch resistance calculation is facilitated by the simple rectangular geometry. In solving for the resistance, the switch electric field, trap concentration, and free carrier concentration are assumed to be uniform. This approximation is made on the basis of a uniform illumination across the switch, and a long optical absorption length relative to the dimensions of the sample. The computer code calculates the effect of the field dependent mobility by finding this average electric field in a particular incremental time interval. This value is then used to calculate the field-dependent mobility used in the next incremental time interval. The values for hole mobility were obtained from the velocity vs. field curves found in ref. (11). The values for

electron mobility at high field were also obtained from ref. (11), but the low-field electron mobility used was determined by Hall measurement to be 5000 cm^2/V-s.

EXPERIMENTAL PROCEDURE

The GaAs switches used were illuminated with a Q-switched Nd:Yag laser operating at 1.06 microns. The switching circuit consisted of the GaAs switch, 50 ohm pulse forming line, high voltage power supply and charging resistor, and a 50 ohm load resistor. The photocurrent was monitored using a CT-1 current transformer. The laser pulse shape was monitored using an FND 100 photo diode. Laser pulse energy was measured using a thermopile.

The switches were rectangular prisms with contacts on opposite parallel sides. The contacts covered the entire surface, .4 X .4 cm. The width of the switches, corresponding to the distance between the electrodes, was 0.2 cm. Contacts were made by e-beam deposition of Au:Ge with excess Ni. Contacts also incorporate an Ag diffusion barrier. Switches were polished on both the front (illuminated) and back surfaces.

The liquid encapsulated GaAs was obtained from MA/COM. High-resistivity Hall measurements were taken on material from the same wafer as the switches. From the resistivity, mobility and free-carrier concentration measurements, we were able to estimate the EL 2 occupation. The low field mobility value used in the code was obtained from the manufacturer's specification. The EL 2 concentration was estimated by absorption measurements taken on material from the same wafer as the switches, using a Cary 17B spectrophotometer.

The laser intensity was varied with neutral density filters. Peak laser power was calculated from the pulse energy and laser waveform. Unattenuated energy was 10 mJ, corresponding to 250 kW/cm^2. Measurements were also taken at 1.0% and .1% intensity, corresponding to 2.5 and .25 kW/cm^2. The laser waveform is shown in Fig. 1.

Bias voltage was varied from 200 to 3000 volts. The pulse forming line maintains a constant bias on the switch/load branch for only 85 nS (approximately). After this, the bias is changed by reflections. Computed waveforms are valid for the 85 nS interval only.

COMPARISON OF EXPERIMENTAL RESULTS & COMPUTED VALUES

Figures (2) and (3) show the experimental 1 kV waveforms at 0.1% and 1.0% laser intensity. Figures (4) and (5) are corresponding computed waveforms (it is reminded that the computed waveform is only valid up to the PFL pulsewidth, 85 ns).

The computer generated load voltage waveforms were calculated using the estimated HL10 and EL6 trap concentrations which gave the best fit to the experimental data. For HL10 we used 1 X 10^{16} ($/cm^3$), and for EL6, 5 X 10^{16}. As previously indicated, the HL10 may be considered representative of certain hole traps, and the EL6 of certain electron traps. The EL2 concentration, 1.77 X 10^{16}, was measured by IR absorption.

While the simulation reflects the trend of faster recovery at lower illumination, the predicted recovery is still much slower than the observed recovery, particularly in regard to the long tail, which is for the most part comprised of hole current. Apparently, an additional trap (not EL2, EL6, or HL10) is responsible for the faster recovery, one that should be highly effective in capturing holes.

CONCLUSIONS

Photo-conductivity in semi-insulating GaAs, at 1.06 microns, has been modeled using three of the more prominent traps reported in the literature. These are: EL2, EL6, and HL10. Comparison of the computer and experimental waveforms shows a discrepency in the recovery time, possibly indicating the existance of an unspecified, prominent trap, particularly one effective in capturing holes. Incorporation of updated trap data into the model, and further comparisons with experiment, are planned.

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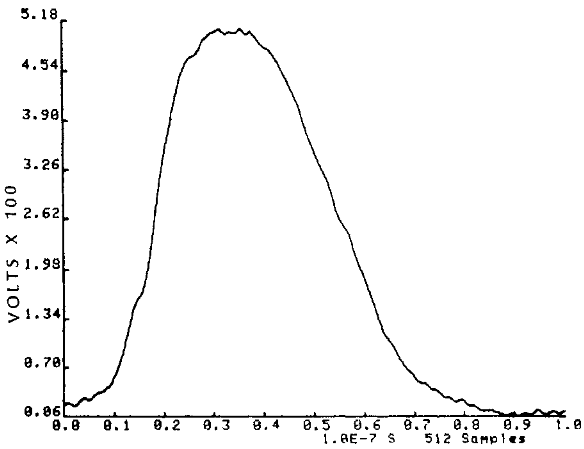

FIG. 3 LOAD VOLTAGE vs. TIME

1.0 kV. bias, 1.0% laser intensity

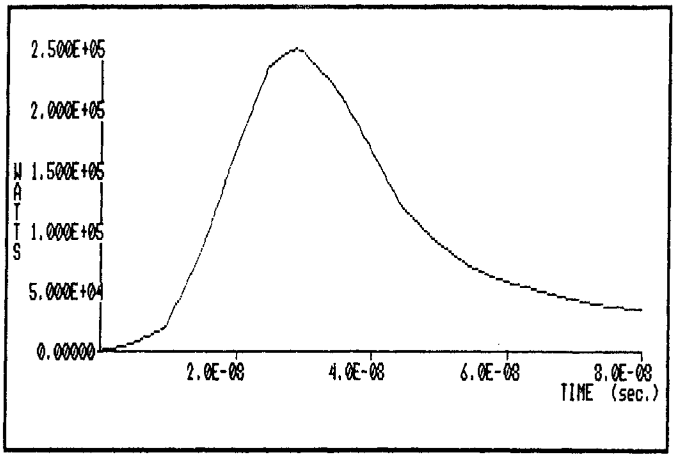

FIG.1: LASER POWER vs. TIME

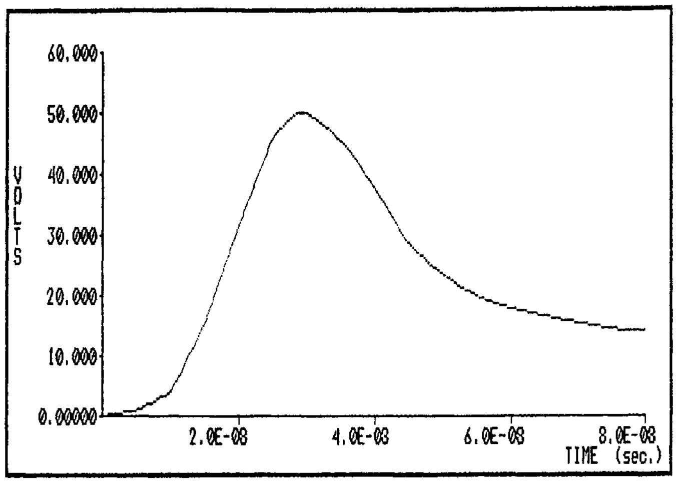

FIG.4: LOAD VOLTAGE vs. TIME (1.0 kV. BIAS, .1% LASER INTENSITY)

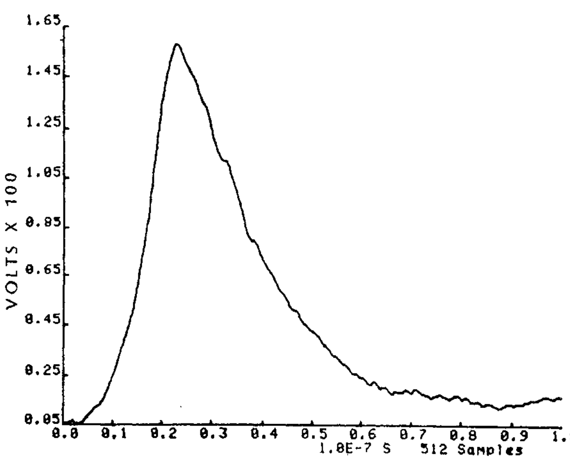

FIG. 2. LOAD VOLTAGE vs. TIME

1.0 kV. bias, .1% laser intensity

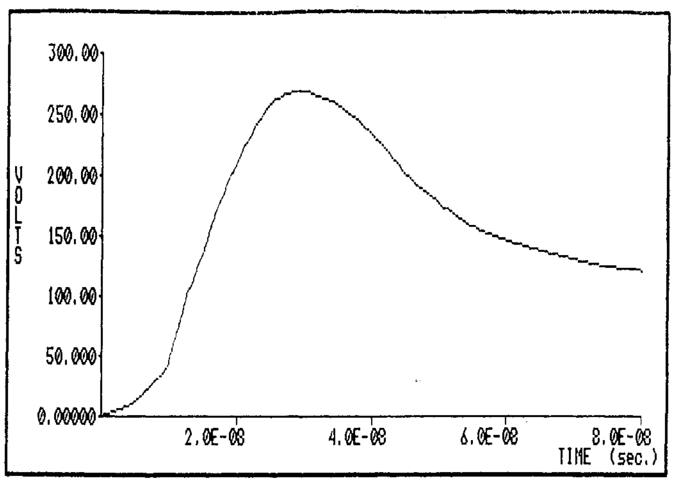

FIG.5: LOAD VOLTAGE vs. TIME (1.0 kV. BIAS, 1.0% LASER INTENSITY)